Mass hierarchy determination using current and upcoming neutrino experiments

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Abstract. Determination of mass hierarchy is a crucial open ended question in neutrino physics today. In the wake of recent T2K [1], MINOS [2] and DChooz [3] results which support a high best-fit to θ_{13}, it is worthwhile to explore the potential of the upcoming and already running neutrino experiments for determining mass hierarchy. We consider the long baseline experiments NOνA and T2K and the reactor neutrino experiments Daya Bay, DChooz and RENO. In our analysis we find out that NOνA by itself is insufficient and would require another long baseline experiment such as T2K. This work assumes that by the time reactor neutrino experiments are over, we will have a precise θ_{13} information. Final results are presented as hierarchy exclusion plots in $\sin^2 2\theta_{13} - \delta_{CP}$ plane.

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1. Introduction

The electron appearance probability is the best bet to find out the unknowns in neutrino physics as it is sensitive to all the neutrino parameters.

$$\begin{aligned}\mathcal{P}\left(\nu_\mu \to \nu_e\right) &= \sin^2 2\theta_{13}\sin^2\theta_{23}\frac{\sin^2\hat{\Delta}(1-\hat{A})}{(1-\hat{A})^2} + \alpha^2\sin^2 2\theta_{12}\cos^2\theta_{13}\cos^2\theta_{23}\frac{\sin^2\hat{\Delta}\hat{A}}{\hat{A}^2} \\ &\quad +\alpha\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\cos(\hat{\Delta}+\delta_{CP})\frac{\sin\hat{\Delta}\hat{A}}{\hat{A}}\frac{\sin\hat{\Delta}(1-\hat{A})}{1-\hat{A}}\end{aligned}$$

where $\hat{\Delta} = \Delta_{31}L/4E$, $\hat{A} = A/\Delta_{31}$, $\alpha = \Delta_{21}/\Delta_{31}$. Here $A = 2EV_{CC}$; where V_{CC} is the matter dependent potential. In this work, we address the question of finding out the sign of Δ_{31}. This is termed as neutrino mass hierarchy: Normal ($\Delta_{31} > 0$) or Inverted ($\Delta_{31} < 0$).

2. Problem of degeneracy

The problem with the electron appearance channel is that it is plagued with degeneracies. That is one can have a situation where

- P(NH, ${\theta_{13}}^1$)=P(IH, ${\theta_{13}}^2$) for the same δ_{CP}: hierarchy-θ_{13} degeneracy
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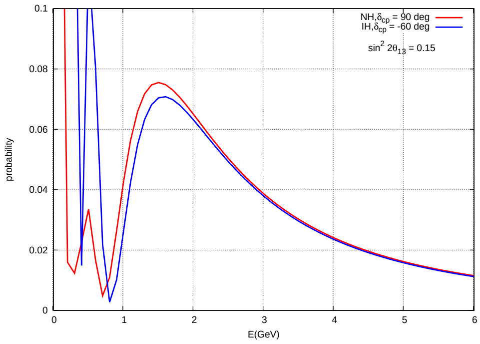

Figure 1. Plot showing the hierarchy-δ_{CP} degeneracy for NOνA.

Figure 1 shows hierarchy-δ_{CP} degeneracy. Here it is shown that P(NH, ${\delta_{CP}}^1 = 90°$) $\sim$ P(IH, ${\delta_{CP}}^2 = -60°$) for $\sin^2 2\theta_{13} = 0.15$. One can generate a similar plot for hierarchy-θ_{13} degeneracy. Since all three parameters (θ_{13}, δ_{CP} and hierarchy) are unknown, measurement becomes very difficult. However there are ways in which this problem can be handled.

3. Reactor neutrino experiments: Daya Bay, DChooz and RENO

The reactor neutrino experiments intend to measure a non-zero value of θ_{13}. They will use the electron disappearance channel which is independent of CP violating phase δ_{CP}. These experiments are built for very short baselines (very small matter effects) and therefore are insensitive to hierarchy-δ_{CP} degeneracy. This makes an independent θ_{13} measurement possible. The proposed reactor neutrino experiments are Daya Bay, DChooz and RENO.

4. Long baseline experiments: NOνA and T2K

The long baseline experiments considered are the ones which are sure to be installed as of now viz. NOνA and T2K. A brief description of the two experiments follow. Greater details can be found from their websites [4][5]. NOνA will use the NuMI beam from Fermilab which peaks around 1.6 GeV. The detector for NOνA is a Totally Active Scintillator Detector (TASD) of 15 kton fiducial volume, placed 810 km away from the beam source. The beam consists primarily of muon neutrinos and NOνA will look for electron events in the detector. The NuMI beam power has been assumed to be 0.7 MW. For T2K, a beam peaking at 0.6 GeV will come from the J-PARC accelerator at Tokai. A 22.5 kton fiducial volume Water Cerenkov detector is placed 295 km away at Kamioka. T2K will also look for electron neutrinos in a beam which was initially muon neutrinos. The beam power for T2K has been assumed to be 750 MW.

5. Simulation details

We use the software GLoBES [6][7] for our analysis. The runtime for NOνA is $(6\nu+3\bar{\nu})$ for all the plots shown. The runtime for T2K is $(3\nu+4\bar{\nu})$ for all the plots shown. Only electron appearance events have been considered as signal events. The backgrounds for this channel is formed by misidentified muons, NC events and intrinsic beam ν_e. We have done marginalization wherever required. Priors were added for θ_{13}, θ_{23} and Δ_{31} with $\sigma\left(\sin^2 2\theta_{13}\right) = 0.01$, $\sigma\left(\sin^2 2\theta_{23}\right) = 0.02$ and $\sigma\left(\Delta_{31}\right) = 0.03 \times (\Delta_{31})$. A prior of $\sigma\left(\sin^2 2\theta_{13}\right) = 0.01$ effectively takes into account the data due to reactor neutrinos experiments. We have taken care in defining Δ_{31}^{NH} and Δ_{31}^{IH} in terms of the measured quantity Δ_{atmos}.[8]

$$\Delta_{31} = \Delta_{atmos} + \left(\cos^2\theta_{12} - \cos\delta \sin\theta_{13} \sin 2\theta_{12} \tan\theta_{23}\right) \Delta_{21}$$

where $\Delta_{atmos} = \pm 2.4 \times 10^{-3} \mathrm{eV}^2$; + for NH, - for IH. We have assumed a 5% systematics uncertainty on both signal and background.

6. Hierarchy exclusion plots

The following plots show the hierarchy excluding capabilities.

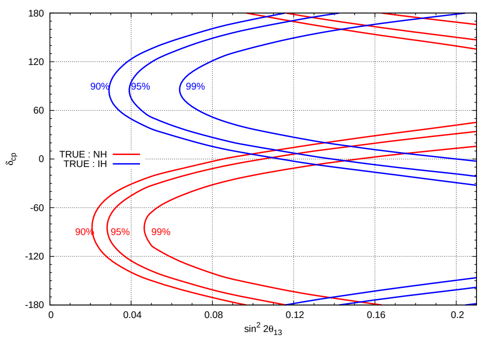

Figure 2. Hierarchy exclusion plots (without systematics) for NOνA only.

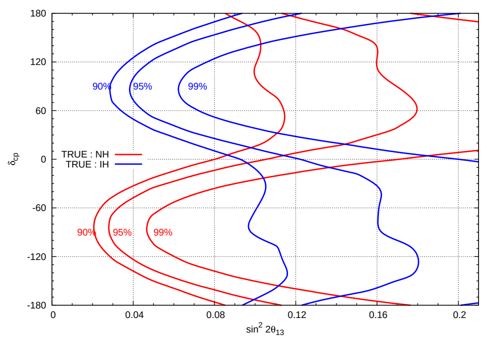

Figure 3. Hierarchy exclusion plots (with systematics) for the combined setup of NOνA and T2K.

The plots show different confidence level regions and for all ($\delta_{CP} - \sin^2 2\theta_{13}$) points on the right of a line, the wrong hierarchy can be excluded from the right hierarchy with that confidence level. It can be seen from this plot that NOνA performs very well only for a particular range of true δ_{CP} depending on the true mass hierarchy. For NH, this range is $-120°$ to $-60°$ and for IH, this range is $60°$ to $120°$. In δ_{CP} ranges other than these, NOνA does not perform well because of the hierarchy-δ_{CP} degeneracy. Similar studies were also done in [9].

7. How and why does T2K data help?

It can be seen from figure 3 that at 90% C.L., T2K data boosts significantly NOνA's ability for determining mass hierarchy for NH as the true hierarchy in the upper half plane (UHP) of [0,180°] and for IH in the lower half plane (LHP) of [-180°,0]. This can be understood by analysing the error plots (figures 4 and 5) due to individual runs of NOνA and T2K with NH as the true hierarchy and IH as the test hierarchy for the following true points: $\sin^2 2\theta_{13} = 0.05$, $\delta_{CP} = -90°$ and $\sin^2 2\theta_{13} = 0.15$, $\delta_{CP} = 90°$. For NH as the true hierarchy, the favorable plane for NOνA is LHP.

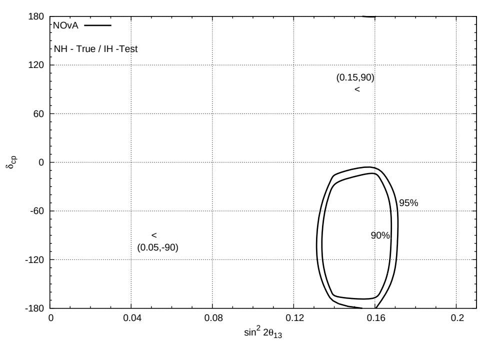

Figure 4. Error plots: NOνA.

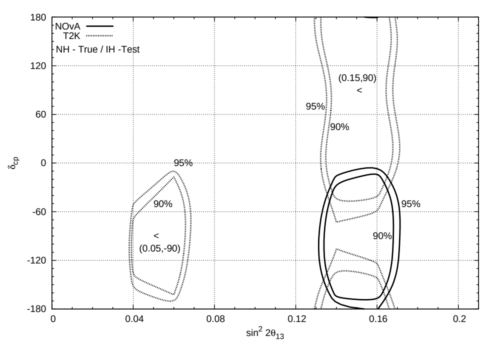

Figure 5. Error plots: NOνA and T2K; individually.

In LHP, NOνA by itself performs very well and T2K data does not have significant effects.

This is evident from the error plots. For the true point ($\sin^2 2\theta_{13} = 0.05$, $\delta_{CP} = -90°$) (δ_{CP} in the LHP), there is no error in the NOνA measurements (no contours at 90% and 95% C.L.). However when the true point is $\sin^2 2\theta_{13} = 0.15$, $\delta_{CP} = 90°$ (δ_{CP} in the UHP), NOνA gives totally wrong results. True point lies out of 90% and 95% C.L. contours. A wrong hierarchy and wrong δ_{CP}-plane fakes the true point. This is hierarchy-δ_{CP} degeneracy. However the error plots for T2K correctly predicts the true point. This is because it experiences less hierarchy-δ_{CP} degeneracy as it is a shorter baseline and appreciable matter effects do not develop. Thus T2K data provide the additional $\Delta\chi^2$ at the wrong hierarchy-wrong δ_{CP} point thereby increasing the sensitivity to hierarchy exclusion. This point can be elaborated more by figures 6 and 7 (for an updated analysis, see [10]).

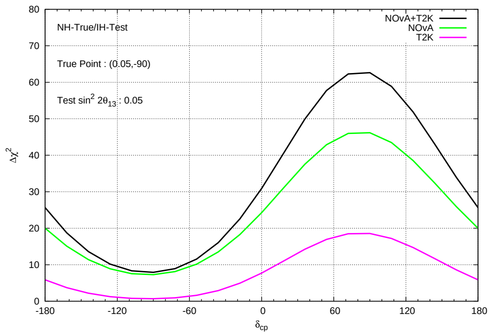

Figure 6. $\Delta\chi^2$ vs. δ_{CP} for $\sin^2 2\theta_{13} = 0.05$, $\delta_{CP} = -90°$: Moving along $\sin^2 2\theta_{13} = 0.05$ in the error plot plane.

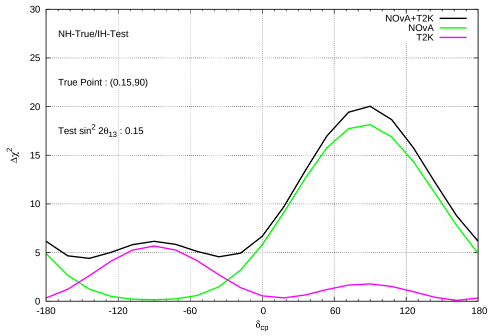

Figure 7. $\Delta\chi^2$ vs. δ_{CP} for $\sin^2 2\theta_{13} = 0.15$, $\delta_{CP} = 90°$: Moving along $\sin^2 2\theta_{13} = 0.15$ in the error plot plane.

8. Results

The exclusion plots show that the combined setup of the LBL experiments - NOνA and T2K and the reactor neutrino experiments will be able to exclude the wrong hierarchy from the right one @ 90%C.L. for all δ_{CP} provided $\sin^2 2\theta_{13} > 0.115$. This is the best that we can achieve with the present statistics.

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